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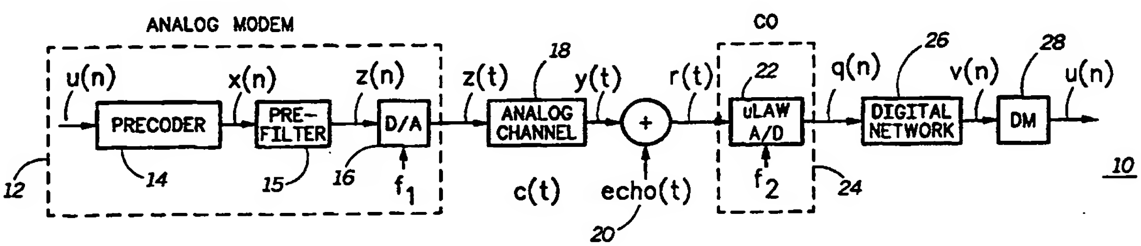

(57) Abstract

A transmitter in an analog pulse code modulation (PCM) modem (12) which transmits analog levels over an analog channel (18) to produce constellation points at a quantization device (26), wherein the constellation points correspond to groups of data bits to be transmitted to a digital PCM modem (28), the transmitter includes: a transmitter device which selects for each group of data bits to be transmitted a constellation point corresponding to the group of data bits and transmits over the analog channel a level that will produce at the input to the quantization device the selected constellation point; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points that have substantially equivalent, minimized error probability, constellation point to constellation point.

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SYSTEM, DEVICE AND METHOD FOR PCM UPSTREAM TRANSMISSION UTILIZING AN OPTIMIZED TRANSMIT CONSTELLATION

Field of the Invention

This invention relates to PCM upstream transmission and more particularly to a system, device and method for PCM upstream transmission utilizing an optimized transmit constellation.

Background of Invention

Conventional modems, such as V.34 modems, treat the public switched telephone network (PSTN) as a pure analog channel even though the signals are digitized throughout most of the network. In contrast, pulse code modulation (PCM) modems take advantage of the fact that most of the network is digital and that typically central site modems, such as those of internet service providers and on-line services, are connected to the PSTN via digital connections (e.g., T1 in the United States and E1 in Europe). First generation PCM modems transmit data in PCM mode downstream only (i.e., from a central site digital modem to an analog end user modem) and transmit in analog mode, e.g. V.34 mode, upstream (i.e., from the end user modem to the central site modem). Future generation PCM modems will also transmit data upstream in PCM mode.

With PCM downstream, the central site PCM modem transmits over a digital network eight bit digital words (octets) corresponding to different central office codec output levels. At the end user's central office, the octets are converted to analog levels which are transmitted over an analog loop. The end user's PCM modem then converts the analog levels into equalized digital levels. The equalized digital levels are ideally mapped back into the originally transmitted octets and the data the octets represent. With PCM upstream, the end user PCM modem transmits analog levels over the analog loop corresponding to the data to be transmitted and the levels are

quantized to form octets by a codec in the end user's central office. The codec transmits the octets to the PCM central site modem over the digital network.

However, due to impairments in the digital network, such as digital trunk loss (in the US, typically 0, 3 or 6 dB) caused by digital padding and robbed bit signaling (hereinafter referred to as RBS), caused by the networks in-band signaling, the octets transmitted both in the upstream and downstream directions may be corrupted. If not accounted for, this can cause high data error rates in the modems.

Methods for effectively detecting and mitigating downstream digital impairments are known. Examples of these methods are described in the following co-pending applications, assigned to the assignee of the present invention: US Patent Application 08/885,710, Scull, Christopher J.T.; Burch, Richard A; System, Device and Method for Detecting and Characterizing Impairments in a Communication Network; filed 6/30/97; US Patent Application 08/730,433. Eyuboglu, M. Vedat; Barabell, Arthur J.; Humblet, Pierre A.; System And Device For, And Method Of, Detecting, Characterizing, And Mitigating Deterministic Distortion In A Communications Network; filed 10/15/96.; US Patent Application entitled, System, Device and Method for Detecting Impairments in a Communication Network, Attorney Docket No. UD097017, filed 11/26/97; and US Patent Application entitled, Apparatus, System And Method For Transmitting And Receiving A Training Sequence Optimized For Detecting Impairments In A Communication Network, Attorney Docket No. CX097023, filed 11/26/97. These applications are incorporated herein in their entireties by reference.

With upstream transmission, quantization and PCM downstream echo, in addition to upstream digital impairments, add complexity to the PCM encoding and decoding process. In particular, they add complexity to the selection of a constellation of transmit points (transmit constellation) for various upstream channel conditions. Several PCM upstream transmit constellations, for data rates of 24-40 kbps, have been proposed. See Telecommunications Industry Association (TIA), Technical Committee TR-30.1, Committee Contribution Document Number: TR-30.12/96, Proposed Baseline for PCM Upstream, Nuri Dagdeviren (Lucent Technologies), December 4-5, 1996. With these constellations, it is indicated that the effects of hybrid echo and analog loop loss were the primary focus. Thus,

depending on the detected echo and analog loop characteristics, a constellation is selected for upstream transmission. However, for their given data rates these constellations do not have optimal error probability (probability that the transmitted constellation points will be improperly decoded by the digital modem). In order to decrease the error probability, the data rate must be sacrificed. Moreover, these constellations are not designed to account for upstream digital impairments encountered in the digital network.

Therefore, a need exists for a system, device and method for PCM upstream transmission by an analog PCM modem utilizing an optimized transmit constellation, wherein the transmit constellation is designed with non-uniformly spaced constellation points having substantially equivalent, minimized error probability, point to point, to enable decoding by a digital PCM modem of the constellation points in the presence of PCM downstream echo, quantization and digital impairments while maintaining increased data rates.

Brief Description of the Drawings

FIG. 1 is a block diagram depicting PCM upstream transmission;

FIG. 2 is an equivalent discrete time block diagram of the block diagram of FIG. 1;

FIG. 3 is a representation of a portion of a μ-law constellation in order to illustrate symbol-by-symbol decoding with a predetermined PCM downstream echo;

FIG. 4 is a representation of a portion of the μ-law constellation of FIG. 3 in order to illustrate symbol-by-symbol decoding with a different predetermined PCM downstream echo;

FIG. 5 depicts a portion of a representation of a μ-law quantizer with a Gaussian noise distribution centered about constellation point y_k;

FIG. 6 depicts certain μ-law quantizer thresholds and how the thresholds are altered in the presence of RBS; and

FIG. 7 is a flow diagram illustrating transmit constellation selection according to this invention.

Detailed Description of a Preferred Embodiment

Bi-directional PCM communication is described in US Application Serial No. 08/724,491, entitled Hybrid Digital/Analog Communication Device, which is assigned to the assignee of the present invention and which is incorporated herein in its entirety by reference. There is shown in block diagram 10, FIG. 1, an example of PCM upstream transmission in such a bi-directional PCM communication system. There is included analog PCM modem 12, having a precoder 14 and a digital to analog converter (D/A) 16, interconnected to analog channel 18. Precoder 14 receives digital data u(n) and outputs precoded digital data x(n). The precoded digital data is provided to prefilter 25 which outputs filtered signal z(n). Filtered signal z(n) is converted to analog form and is transmitted as signal z(t) over analog channel 18, having a channel characteristic, c(t). The analog channel modifies the transmitted signal z(t) to form signal y(t) which then encounters downstream PCM echo, echo(t) 20, that is added to y(t), producing signal r(t). Signal r(t) is received by μ-law (A-law in some countries outside of the US) quantizer 22 in central office (CO) 24 and is quantized according to the μ-law. See International Telecommunications Union, Recommendation G.711, Pulse Code Modulation (PCM) of Voice Frequencies, 1972.

The quantized octets (digital values), q(n), are transmitted over digital network 26 at a frequency of 8kHz where they may be affected by various digital impairments, as discussed below. The possibly affected octets, v(n), are received by digital PCM modem 28 which ideally decodes the octets, v(n), into their corresponding constellation points, y(t), from which the original digital data, u(n), can be derived.

Before data can be transmitted upstream, the clock (f_1) of D/A 16 in analog PCM modem 12 must be synchronized to the clock (f_2) of CO 24. This can be achieved by learning the clock CO 24 from the downstream PCM signal (not shown) and synchronizing the clocks using the technique proposed in US Patent No. 5,199,046, entitled First and Second Digital Rate Converter Synchronization Device and Method, incorporated herein by reference in its entirety. Once the clocks are synchronized, PCM upstream block diagram 10, FIG. 1, can be represented as equivalent discrete time block diagram 10', FIG. 2, with like components being

represented by the same reference numbers containing a prime ('). In block diagram 10' we assume that $f_1 = f_2$; however, it must be noted that f_1 does not have to be equal to f_2 as long as the two clocks are synchronized. When f_1 is equal to f_2, n is the time index for 8kHz samples, since the clock (f_2) of CO 24 is fixed at that frequency.

Precoder 14 (14') and prefilter 15 (15') may be implemented as described in co-pending application entitled Device and Method for Precoding Data Signals for Pulse Code Modulation Transmission, CX096044P02, which is assigned to the assignee of the present invention and which is incorporated herein in its entirety by reference. As explained in co-pending application CX096044P02, digital data u(n) may be sent by transmitting z(n) such that the constellation points y(n) will be one of a number of points in an equivalence class for u(n). The point y(n) in the equivalence class of u(n) that is selected is usually determined to minimize the transmit power which is the power of x(n).

Using the above precoding technique, or another precoding technique, it is difficult to accurately decode u(n) from v(n) in the presence of echo, quantization and digital impairments without a properly designed transmit constellation of points, y(n). It is described below how to design the transmit constellation for y(n) with a certain minimum error probability and a substantially equivalent error probability constellation point to constellation point in order to decode y(n) (and eventually u(n)) from v(n) in the presence of echo, quantization and digital impairments, while maintaining an increased data rate. The constellation design according to this invention is not restricted to the above described precoding schemes and may be utilized with various precoding schemes.

Optimized Constellation Design

Initially, the design of a transmit constellation (points y(n)), according to this invention, is described assuming there are no digital impairments in the digital network 26', FIG. 2, i.e., q(n) = v(n). Then, this technique is generalized in order to demonstrate how the constellation points are selected for a constellation when there are digital impairments in network 26'. The constellations are designed to achieve a

predetermined, minimized error probability which probability is substantially equivalent point to point in the constellation.

The technique for designing an optimized constellation according to this invention is dependent upon the decoding scheme utilized by digital modem 38'. It will first be shown how to design the constellation assuming no channel coding to y(n) and symbol-by-symbol decoding. Then, the constellation design is generalized to the case when there is channel coding to y(n) and the digital modem 38' employs a sequence based decoding scheme, such as a Viterbi decoding algorithm. See, e.g., Lee, A.E., and Messerschmitt, D.G.; "Digital Communication", Kluwer Academic Publishers, 1994.

Symbol-by-Symbol decoding

As an example, it is assumed that $\{y_0, y_1, ..., y_{M-1}\}$ are the M constellation points for y(n). When digital modem 38' receives v(n), and has an estimation of the downstream PCM echo, echo(n) 20', FIG. 2, then digital modem 38' can decode which y(n) has been transmitted by finding the most probable y_i, i.e.:

$$\max_{y_i} \Pr(v(n) \mid y_i, echo(n)) \qquad (1)$$

Assuming no digital impairments, the most probable y_i is the y_i that is closest in value to v(n) - echo(n) and this may be determined as follows:

$$\min_{y_i} \left| v(n) - (y_i + echo(n)) \right| \qquad (2)$$

That is, the most probable y_i is the y_i which minimizes v(n) - (y_i + echo(n)). With digital impairments the most probable y_i may be determined as follows:

$$\min_{y_i} \left| vq(n) - (y_i + echo(n)) \right| \qquad (3)$$

The echo estimation, echo(n), and vq(n), virtual quantizer points, are determined by digital modem 38' , as described in co-pending application entitled Device and Method for Detecting PCM Upstream Digital Impairments in a Communication Network, CX097029, filed on even date herewith and incorporated herein in its entirety by reference.

The decoding process may be better understood by observing the symbol-by-symbol decoding example depicted in FIG. 3. In this figure, the "x" marks in the axis represent μ-law quantized levels and the "I " marks in the axis represent the μ-law threshold levels. As is known in the art, there are 255 μ-law quantized levels which have predefined thresholds. Of course, FIG. 3 depicts only a small portion of all of the possible μ-law quantized levels. In this example, it is assumed that a certain constellation has points $y_4 = 695$ and $y_5 = 730$ and the estimation of the PCM downstream echo, echo(n) is 15.4. If digital modem 38' receives v(n) = 751, it will be determined that y_5 has been transmitted since, in the presence of noise, y_5 has the highest probability of being the transmitted constellation point, given echo(n), as it is the only point falling between the thresholds surrounding μ-law quantized level, v(n)= 751.

Another example using the same constellation points is shown in FIG. 4. In this example, however, the estimation of the PCM downstream echo, echo(n), is 370.1. In this case, for both constellation points, y_4 and y_5, transmitted digital modem 38' will receive v(n) = 1087. As a result, digital modem 38' may have difficulty distinguishing between constellation points y_4 and y_5 and, therefore, there is a high error probability for these constellation points.

The transmit constellation should be designed such that this kind of error, which occurs when y(n) + echo(n) falls where the step size is large for the μ-law quantizer, occurs rarely enough to achieve some target minimized error probability (e.g., $P_e = 10^{-6}$). This can be achieved by increasing the distance between the constellation points. However, this will reduce the number of points that can be used in the constellation (since there are a finite number of μ-law quantized levels) which

reduces the data rate. And, increasing the distance between the constellation points also increases the overall transmit power in analog modem 12', FIG. 2.

With the constellation design of the present invention it is shown how to achieve the highest data rate (i.e., the largest number of constellation points, y(n)) and still achieve a certain, minimized overall target error probability, and a substantially equivalent error probability point to point. As is shown in the above examples, PCM downstream echo, echo(n), has a significant effect on the error probability of a constellation design. As will be evident from the following constellation design algorithm, different constellations are needed for different echo and noise characteristics (like variance of echo and noise.)

<u>Constellation Design Algorithm for Symbol-by-Symbol Decoding</u>

The constellation design described herein is symmetrical, in that the y_M constellation points are divided into positive constellation points $\{y_0, y_1, \ldots y_{M-1/2}\}$ and negative constellation points $\{-y_{M-1/2} \ldots -y_1, -y_0\}$; however it may be designed asymmetrically. The design algorithm is recursive, i.e., assuming $y_0, y_1, \ldots, y_{k-1}$ have already been determined according to this algorithm, y_k is designed such that the following conditions are satisfied:

$$Pr(\ldots, y_0, y_1, \ldots, y_{k-1} \text{ decoded} \mid y_k \text{ sent})^{\wedge} < (10^{-6})/2 \text{ and} \quad (4a)$$

$$Pr(y_k, y_{k+1}, \ldots \text{ decoded} \mid y_{k-1} \text{ sent})^{\wedge} < (10^{-6})/2 \quad (4b)$$

This assumes that 10^{-6} error probability is the desired target error probability for each point, y_k ,in the constellation. This target error probability is exemplary and other error probabilities could be used. Note that each of the single sided error probabilities, namely, the left hand side (LHS) error probability in equation 4a and the right hand side (RHS) error probability in equation 4b are smaller than half of the target symbol error probability. This guarantees that the double sided error probability is less than the target error probability.

Equation 4a requires that the probability that any points in the constellation which are smaller than the present point, y_k, being selected are decoded given the present point, y_k, being transmitted is less than one half the target error probability. Equation 4b requires that the probability that any points in the constellation which are larger that the previous point, y_{k-1}, are decoded given the previous point, y_{k-1}, being transmitted is less than one half the target error probability.

The Probability Pr(Ö,y_0,y_1,Ö,y_{k-1} decoded I y_k sent) can be calculated as follows:

$$\Pr(\text{Ö},y_0,y_1,..,y_{k-1}\text{ decoded} \mid y_k \text{ sent}) = \int_{-\infty}^{\infty} \Pr(y_0,y_1,\text{Ö},y_{k-1}\text{decoded} \mid y_k \text{ sent}, e)P_E(e)de \quad (5)$$

where e is the PCM downstream echo, echo(n), and should be integrated e = -∞ to ∞. The integration of e can be approximated to a summation of small intervals of e.

For the probability of echo, i.e. $P_E(e)$, we can assume Gaussian distribution (The constellation will be different if we assume a different distribution for echo), which is

$$P_E(e) = \frac{1}{\sqrt{2\pi}\sigma_e}\exp(-\frac{e^2}{2\sigma_e^2}) \quad (6)$$

where σ_e^2 is the echo variance determined by digital modem 28', as described in co-pending application CX097029.

In FIG. 5 there is shown an assumed Guassian distribution for noise 40 centered about the constellation point y_k + echo. The areas 42 and 44 under distribution 40, beyond quantizer thresholds 46 and 48, provide the error probabilities for the LHS and RHS, respectively. For example, the area 42 under curve 40 is the probability that y_k + echo + noise < threshold 46. From FIG. 5, it can determined how to calculate Pr(..,y_0,y_1,Ö,y_{k-1} decoded I y_k sent, e) assuming some distribution for noise (like Gaussian distribution for noise 40), as follows:

$$\Pr(..,y_0,y_1,\text{Ö},y_{k-1} \text{ decoded } | \; y_k \text{ sent}, e) = Q\_fcn\,(((y_k+e)-\text{Threshold}) / \sigma_n) \quad (7)$$

See, e.g., Shanmugan, K.S and Breipohl, A.M., "Random Signals : Detection, Estimation, and Data Analysis", John Wiley & Sons, 1988, for the definition of Q_fcn. The variable "Threshold" is the μ-law quantizer threshold where the μ-law level higher (lower) than this threshold will be decoded as y_k (y_{k-1}), such as threshold 46, FIG. 5. The variable σ_n^2 is the variance of noise. This noise can come from additive channel noise, intersymbol interference from imperfect precoding, and imperfect echo estimation. The variance of noise can be calculated as follows.

The noise, σ_n^2, is the noise component right before the μ-law quantizer. The noise consists of three components, namely: i) ISI due to imperfect precoding (i.e. p(n) is not exactly c(n)*g(n)) and/or the estimation of c(n) is not perfect), ii) echo estimation error, and iii) random channel noise.

The calculation of σ_n^2 is consists of three components. The variable σ_n^2 can be calculated as follows:

$$\sigma_n^2 = \sigma_{ISI}^2 + \sigma_{eE}^2 + \sigma_{noise}^2, \quad (8)$$

where σ_{ISI}^2 is the variance of ISI, σ_{eE}^2 is the variance of echo estimation error, and σ_{noise}^2 is the variance of random channel noise. The variance of ISI can be calculated in the analog modem as follows:

$$\sigma_{ISI}^2 = E_x \| g * c - p \|^2 \quad (9)$$

where Ex is the power of x. We can use -9dBm/$|g|^2$ which is the limit imposed by FCC or some other limit like -10dBm/$|g|^2$ that we intend to use. Note that this does not include the error term due to imperfect estimation of c(n). We can increase σ_{ISI}^2 to take this into account.

The terms $\sigma_{eE}^2 + \sigma_{noise}^2$ are typically calculated in the digital modem as follows. We assume the digital impairments have been detected. In half duplex mode, from the received signal v(n), we first find out the candidates for r(n). For example, if RBS1=No RBS, digital loss=0dB, RBS2=1, then for one v(n), we have two possible r(n)'s. For each v(n), calculate d(n) which is d(n) = r(n) - $\hat{e}(n)$ where r(n) is chosen to give smaller absolute value for d(n) and $\hat{e}(n)$ is the estimated echo. Since d(n) not only contains the echo estimation error and random channel noise but also contains the quantization noise. Therefore, we have to take this into account as follows:

$$\sigma_{eE}^2 + \sigma_{noise}^2 = \sigma_d^2 - \sigma_q^2, \tag{10}$$

where σ_q^2 is the quantization noise variance. This can be calculated as the average of quantization noise variance of each r(n).

$$\sigma_q^2 = \frac{1}{N}\sum_{n=0}^{N-1}(stepSize(r(n)))^2 \Big/ 12 \tag{11}$$

where step size(r(n)) is the µ-law quantization step size where r(n) resides. For example, if r(n)=99 in linear value then step size(r(n))=8.)

We can run the above $\sigma_{eE}^2 + \sigma_{noise}^2$ calculation algorithm only when |r(n)| ≤ MAX, e.g. MAX=93 which will make step size(r(n)) ≤ 4, to make it more accurate.

From equations (5), (6) and (7) above, the Probability Pr(Ö,y_0,y_1,Ö,y_{k-1} decoded | y_k sent) is as follows:

$$\int_{-\infty}^{\infty} Q\_fcn\left(\frac{y_k + e - Threshold}{\sigma_n}\right)\frac{1}{\sqrt{2\pi}\sigma_e} e^{\frac{-e^2}{2\sigma_e^2}} de \tag{12}$$

where equation (12) is approximated as follows:

$$\frac{\Delta}{2M+1}\sum_{j=-M}^{M} Q\_fcn\left(\frac{y_k + j\Delta - Threshold}{\sigma_n}\right)\frac{1}{\sqrt{2\pi}\sigma_e} e^{\frac{-(j\Delta)^2}{2\sigma_e^2}} \tag{13}$$

The integration of equation (12) can be approximated to a summation of small intervals of e as illustrated in equation (13). M is chosen large enough such that $e^{\frac{-(M\Delta)^2}{2\sigma_e^2}}$ is approximately equal to zero. See, e.g., Kreystig, E., "Advanced Engineering Mathematics", John Wiley & Sons, 1983.

The RHS error probability can be calculated in the same way to determine the present point, y_k. This recursive process continues until y_k reaches the largest point that μ-law can support which is 8031. Since it is a recursive algorithm, the initial constellation points $-y_0, y_0$ must be determined first. This can be done by finding y_0 that satisfies the following conditions:

$$\Pr(-y_0 \text{ decoded} \mid y_0 \text{ sent}) < (10^{-6})/2 \text{ and} \quad (14a)$$
$$\Pr(y_0 \text{ decoded} \mid -y_0 \text{ sent}) < (10^{-6})/2 \quad (14b)$$

Again, this assumes that 10^{-6} error probability is the desired target error probability for each point y_k in the constellation. Note that each of the single sided error probabilities, namely, the left hand side (LHS) error probability in equation 14a and the right hand side (RHS) error probability in equation 14b are smaller than half of the target symbol error probability. This guarantees that the double sided error probability is less than the target error probability. Equation 14a requires that the probability that $-y_0$ is decoded given that y_0 is transmitted is less than one half the target error probability. Equation 14b requires that the probability that y_0 is decoded given that $-y_0$ is transmitted is less than one half the target error probability.

The constellation design algorithm according to this invention for designing a constellation with points $\{-y_{M-1/2}, \ldots, -y_2, -y_1, -y_0, y_0, y_1, y_2, \ldots y_{M-1/2}\}$ given an echo, echo(n), having a variance σ_e^2 and a noise variance, σ_n^2, may be summarized as follows:

1) Find y_0 that satisfies:

$\Pr(-y_0 \text{ decoded} \mid y_0 \text{ sent}) < 10^{-6}/2$ and $\Pr(y_0 \text{ decoded} \mid -y_0 \text{ sent}) < 10^{-6}/2$;

2) let k=1 initially;

3) Find y_k that satisfies

$Pr(..,y_0,y_1,...,y_{k-1}$ decoded | y_k sent) < $10^{-6}/2$ and $Pr(y_k,y_{k+1},...$ decoded | y_{k-1} sent) < $10^{-6}/2$; and

4) If y_k < MAX_CONSTELL_LEVEL (e.g. 8031), k=k+1 and Go to 3) else STOP.

There is shown in Table 1 an example of a constellation assuming $\sigma_n = 7$, and $\sigma_e = 150$ and in the presence of no digital impairments. Only the positive constellation points are shown. It is preferred that the values for y(n) be integers; however, this is not required.

Table 1

37, 113, 192, 275, 361, 450, 544, 646, 755, 870, 988, 1108, 1229, 1351,1479, 1634, 1804, 1982, 2164, 2348, 2532, 2716, 2900, 3084, 3268, 3452, 3722, 4022, 4331, 4640, 4949, 5258, 5567, 5876, 6185, 6494, 6803, 7112, 7422, 8287

Constellation Design Algorithm for Channel Coded y(n) and Sequence Decoding

For channel coding and sequence decoding, the same constellation design algorithm may be used. The only difference is in how to calculate the LHS and RHS error probabilities delineated above in equations 4a and 4b. These calculations will depend on the particular code being used and those skilled in the art will be able to make the appropriate calculations given the coding being used.

However, if calculating the error probability in the presence of coding is too difficult, or not desired, then the error probability bound instead of the real error probability may be used. A good error probability bound can be found in the

following references: Viterbi, A.J.; Omura, J.K.; Principles of Digital Communication and Coding, McGraw-Hill, 1979; and Herzberg, H.; Saltzberg, B.R.; Coding for a Channel with Quantization in the Presence of an Estimable Interference, IEEE Transactions on Communications, vol. 45, pp.45-51 , January 1997.

With sequence based decoding y(n) may be decoded as follows: y(n-D), y(n-D-1),..., y(n-D-N_y), is chosen to minimize the following equation:

$$Pr(v(n),v(n-1),...,v(n-N_v)|\ y(n-D),...,y(n-D-N_y),\ echo(n),...,echo(n-N_e)) \quad (15)$$

The exact calculation of this probability is very complex and therefore, in practice, a less complex algorithm like the Viterbi algorithm may be used.

In Herzberg, H. and Saltzberg. B.R., "Coding for a Channel with Quantization in the Presence of an Estimable Interference", IEEE Transactions on Communications, Vol. 45, No. 1, January 1997, coding for upstream mode, assuming a constellation of μ-law levels, is described. The constellations according to this invention do not necessarily use μ -law levels; however, the coding theories are readily applicable to these constellations.

<u>Constellation Design when there is Digital impairment in the Digital Network</u>

The above description of constellation design according to this invention does not account for digital impairments in the digital network. The detection of upstream digital impairments (i.e. RBS and digital loss) is described in co-pending application CX097029. The upstream digital impairments detected by digital modem 28' are communicated to analog modem 12'. Then, using the detected digital impairments and μ-law quantizer 22' a new quantizer, i.e., new threshold levels, can be modeled. For example, if there is odd robbed bit signaling (RBS) in digital network 26', i.e. the type that forces the least significant bit of the affected octets to a "1", then the original μ-law quantizer, see partial representation 50, FIG. 6, is modified to account for RBS to form a new equivalent quantizer, see partial representation 60, FIG. 6. The same constellation design algorithm, as described above, is used but with the new equivalent quantizer thresholds.

An equivalent quantizer can be modeled in the same manner for any RBS and digital loss combination in the upstream channel detected by digital modem 28'.

A symbol-by-symbol decoder in digital modem 28', will work in the presence of digital impairments as follows. Once it receives v(n), it can determine the possible range of r(n) as it will have the equivalent quantizer. From the range of r(n), the decoder can determine which constellation point, y_i, was the most likely transmitted point, as described above in equations (1)-(3) above, and from the constellation point the transmitted data, u (n), can be recovered. Sequence based decoding in the presence of digital impairments may be similarly accomplished and will be apparent to those skilled in the art..

There is shown in Table 2 an example of a constellation for use when RBS is present in digital network 26'. Note that the constellation is the same with LSB=0 and LSB=1 because the equivalent quantizer thresholds are the same for both RBS conditions. The constellation design also assumes that $\sigma_n = 7.0$, and $\sigma_e = 150.0$. Only the positive constellation points are shown.

Table 2

49, 152, 262, 378, 520, 682, 856, 1036, 1219, 1403, 1673, 1973, 2282, 2591, 2900, 3209, 3518, 4056, 4620, 5184, 5747, 6309, 6871, 7434, 8287

Constellation Selection

For data mode, i.e. when analog modem 12' transmits data to digital modem 28', one transmit constellation of a number of constellations that have been predetermined according to the above described algorithm for various digital impairments, noise variance, σ_n^2, and echo variance, σ_e^2, is selected for transmission of data for each RBS time slot. The selection of the transmit constellations may be done by either the analog modem or the digital modem.

In a preferred embodiment, digital modem 28' determines and transmits to analog modem 12' the type of digital impairments affecting the upstream channel and the echo variance. Then, since the calculation of the noise variance, σ_n^2, is

complex it is done partially in digital modem 28' ($\sigma_{eE}^2 + \sigma_{noise}^2$) and partially in analog modem 12' (σ_{ISI}^2). It is possible that the noise variance, σ_n^2, be calculated completely in the digital modem. From the digital impairments, echo varaince and noise variance a transmit constellation is selected for each time slot.

As depicted in flow diagram 100, FIG. 7, the digital impairments, echo variance, σ_e^2, and $\sigma_{eE}^2 + \sigma_{noise}^2$ are obtained, step 102. In step 104, using $\sigma_{eE}^2 + \sigma_{noise}^2$ the noise variance, σ_n^2, is calculated. In step 106, the digital impairments and σ_e^2 and σ_n^2 are compared to stored sets of digital impairments and quantized values for σ_e^2 and σ_n^2. For each stored set there is stored a pre-calculated constellation and for each RBS time slot a stored constellation is selected based on the comparisons. The selected constellations are those with the stored digital impairments and stored σ_e^2 and σ_n^2 having values greater than the calculated σ_e^2 and σ_n^2.

It should be noted that this invention may be embodied in software and/or firmware which may be stored on a computer useable medium, such as a computer disk or memory chip. The invention may also take the form of a computer data signal embodied in a carrier wave, such as when the invention is embodied in software/firmware which is electrically transmitted, for example, over the Internet.

The present invention may be embodied in other specific forms without departing from the spirit or essential characteristics. The described embodiments are to be considered in all respects only as illustrative and not restrictive. The scope of the invention is, therefore, indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range within the equivalency of the claims are to be embraced within their scope.

What is claimed is:

Claims

1. A transmitter in an analog pulse code modulation (PCM) modem which transmits analog levels over an analog channel to produce constellation points at a quantization device, wherein the constellation points correspond to groups of data bits to be transmitted to a digital PCM modem, the transmitter comprising:

a transmitter device which selects for each group of data bits to be transmitted a constellation point corresponding to the group of data bits and transmits over the analog channel a level that will produce at the input to the quantization device the selected constellation point; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points that have substantially equivalent, minimized error probability, constellation point to constellation point.

2. The transmitter of claim 1 wherein the transmitter device includes:

a precoder which receives the groups of data bits to be transmitted and selects for each group a digital level that will produce at the input to the quantizer device the selected constellation point;

a prefilter which filters the digital levels; and

a digital to analog converter, interconnected to the prefilter and the analog channel, which converts the filtered digital levels received from the prefilter to analog levels and transmits the analog levels over the analog channel.

3. The transmitter of claim 1 wherein the transmit constellation is selected from a plurality of predetermined transmit constellations based on upstream digital impairments, echo variance and noise variance.

4 The transmitter of claim 3 wherein a transmit constellation is selected for each of a plurality of robbed bit signalling time slots.

5. In an analog pulse code modulation (PCM) modem which transmits analog levels over an analog channel to produce constellation points at a quantization device, wherein the constellation points correspond to groups of data bits to be transmitted to a digital PCM modem, a method for transmitting data bits, the method comprising:

selecting for each group of data bits to be transmitted a constellation point corresponding to the group of data bits; and

transmitting over the analog channel a level that will produce at the input to the quantization device the selected constellation point; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points that have substantially equivalent, minimized error probability, constellation point to constellation point.

6. The method of claim 5 further wherein the step of selecting includes:

selecting for each group of data bits a digital level that will produce at the input to the quantizer device the selected constellation point; and

the step of transmitting includes:

filtering the digital levels;

converting the filtered digital levels to analog levels; and

transmitting the analog levels over the analog channel.

7. The method of claim 5 wherein the transmit constellation is selected from a plurality of predetermined transmit constellations based on upstream digital impairments, echo variance and noise variance.

8. The method of claim 6 wherein a transmit constellation is selected for each of a plurality of robbed bit signalling time slots.

9. A computer useable medium having computer readable program code means embodied therein for transmitting data bits for use in an analog pulse code modulation (PCM) modem which transmits analog levels over an analog channel to produce constellation points at a quantization device, wherein the constellation points correspond to groups of data bits to be transmitted to a digital PCM modem, comprising:

computer readable program code means for selecting for each group of data bits to be transmitted a constellation point corresponding to the group of data bits; and

computer readable program code means for transmitting over the analog channel a level that will produce at the input to the quantization device the selected constellation point; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points that have substantially equivalent, minimized error probability, constellation point to constellation point.

10. The computer useable medium of claim 9 wherein the computer readable program code means for selecting includes:

computer readable program code means for selecting for each group of data bits a digital level that will produce at the input to the quantizer device the selected constellation point; and

the computer readable program code means for transmitting includes:

computer readable program code means for filtering the digital levels;

computer readable program code means for converting the filtered digital levels to analog levels; and

computer readable program code means for transmitting the analog levels over the analog channel.

11. The computer useable medium of claim 9 wherein the transmit constellation is selected from a plurality of predetermined transmit constellations based on upstream digital impairments, echo variance and noise variance.

12. The computer useable medium of claim 11 wherein a transmit constellation is selected for each of a plurality of robbed bit signalling time slots.

13. A computer data signal embodied in a carrier wave, wherein embodied in the computer data signal are computer readable program code means for transmitting data bits for use in an analog pulse code modulation (PCM) modem which transmits analog levels over an analog channel to produce constellation points at a quantization device, wherein the constellation points correspond to groups of data bits to be transmitted to a digital PCM modem, comprising:

computer readable program code means for selecting for each group of data bits to be transmitted a constellation point corresponding to the group of data bits; and

computer readable program code means for transmitting over the analog channel a level that will produce at the input to the quantization device the selected constellation point; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points that have substantially equivalent, minimized error probability, constellation point to constellation point.

14. The computer data signal of claim 13 wherein the computer readable program code means for selecting includes:

computer readable program code means for selecting for each group of data bits a digital level that will produce at the input to the quantizer device the selected constellation point; and

the computer readable program code means for transmitting includes:

computer readable program code means for filtering the digital levels;

computer readable program code means for converting the filtered digital levels to analog levels; and

computer readable program code means for transmitting the analog levels over the analog channel.

15. The computer data signal of claim 13 wherein the transmit constellation is selected from a plurality of predetermined transmit constellations based on upstream digital impairments, echo variance and noise variance.

16. The computer data signal of claim 15 wherein a transmit constellation is selected for each of a plurality of robbed bit signalling time slots.

17. A system for transmitting data from analog pulse code modulation (PCM) modem to a digital PCM modem, wherein the analog PCM modem transmits analog levels over an analog channel to produce constellation points that correspond to groups of data bits to be transmitted to a digital PCM modem, the constellation points being affected by a PCM downstream echo and received by a quantization device, wherein the quantization device converts the constellation points to digital values and transmits to the digital PCM modem the digital values over a digital network having impairments, wherein the digital PCM modem is adapted to receive the impaired digital values and decode the impaired digital values to their corresponding constellation points, the system comprising:

an analog PCM modem which selects for each group of data bits to be transmitted a constellation point corresponding to the data bits and transmits over the analog channel a level that will produce at the input to the quantization device the selected constellation point and the PCM downstream echo; wherein the constellation points are chosen from a transmit constellation consisting of a plurality of non-uniformly spaced constellation points with substantially equivalent, minimized error probability, constellation point to constellation point; and

a digital PCM modem which receives the impaired digital values and decodes them to their corresponding constellation points.

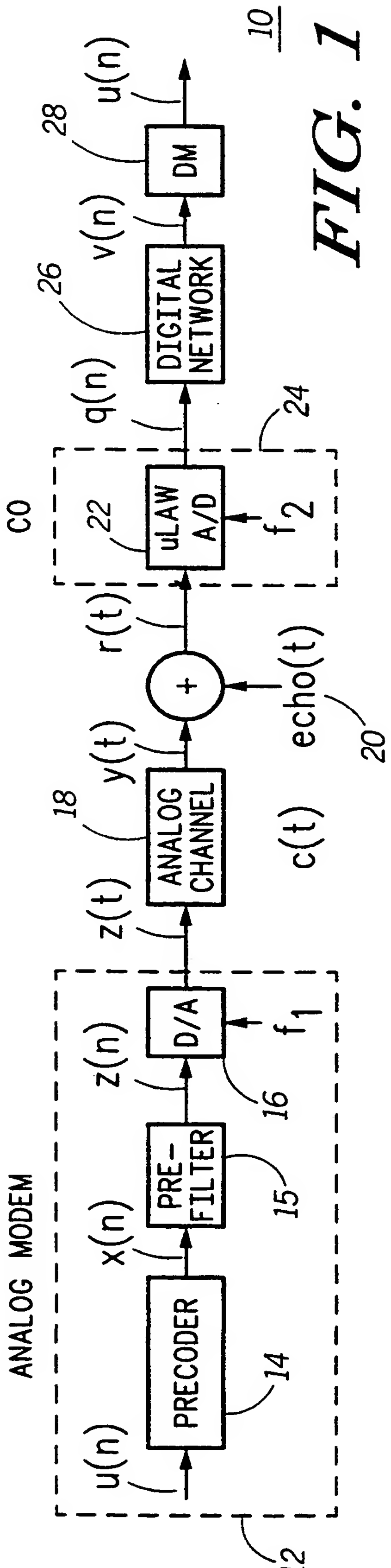
ANALOG MODEM
u(n)
PRECODER
14
x(n)
PRE-FILTER
15
z(n)
D/A
16
f_1
12
z(t)
ANALOG CHANNEL
18
c(t)
y(t)
+
echo(t)
20
r(t)
CO
uLAW A/D
22
f_2
24
q(n)
DIGITAL NETWORK
26
v(n)
DM
28
u(n)
10

FIG. 1

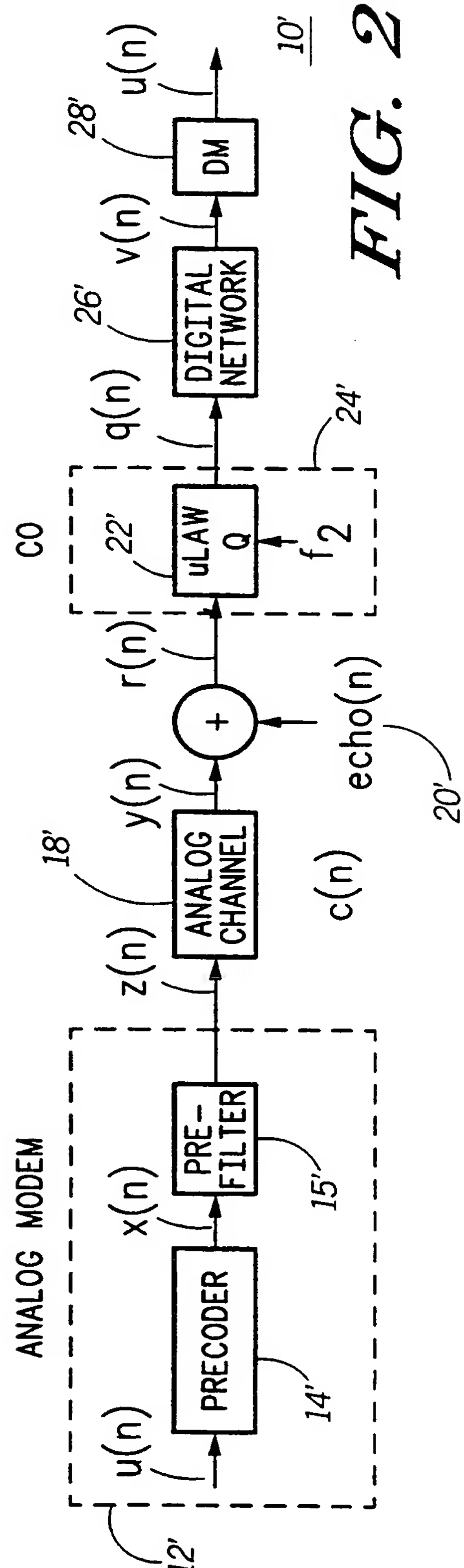
ANALOG MODEM
u(n)
PRECODER
14'
x(n)
PRE-FILTER
15'
12'
z(n)
ANALOG CHANNEL
18'
c(n)
y(n)
+
echo(n)
20'
r(n)
CO
uLAW Q
22'
f_2
24'
q(n)
DIGITAL NETWORK
26'
v(n)
DM
28'
u(n)
10'

FIG. 2

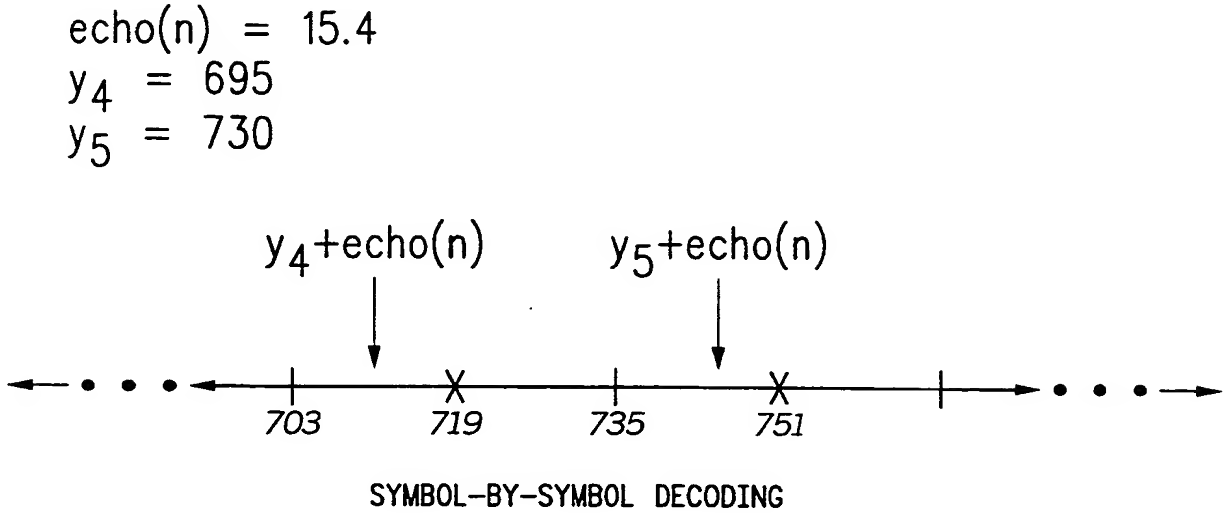
echo(n) = 15.4
y4 = 695
y5 = 730
y4+echo(n)
y5+echo(n)
703
719
735
751
SYMBOL-BY-SYMBOL DECODING

FIG. 3

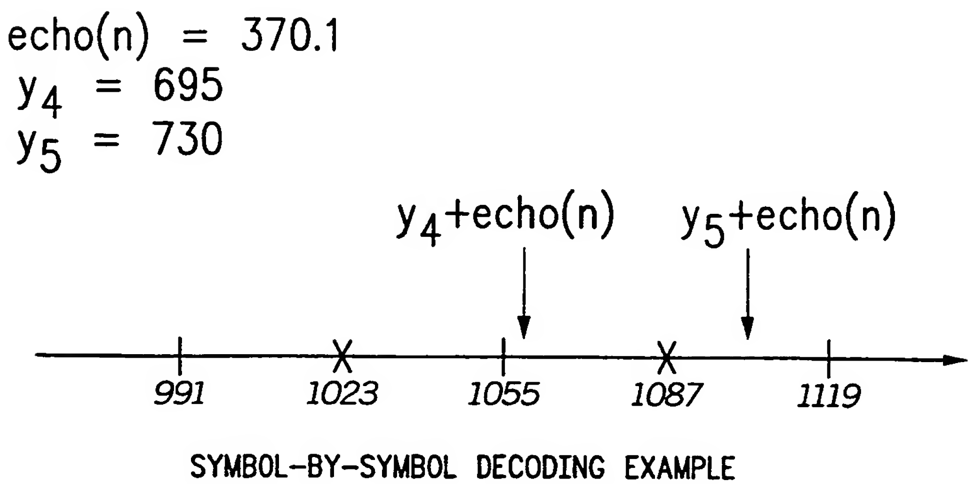
echo(n) = 370.1
y4 = 695
y5 = 730
y4+echo(n)
y5+echo(n)
991
1023
1055
1087
1119
SYMBOL-BY-SYMBOL DECODING EXAMPLE

FIG. 4

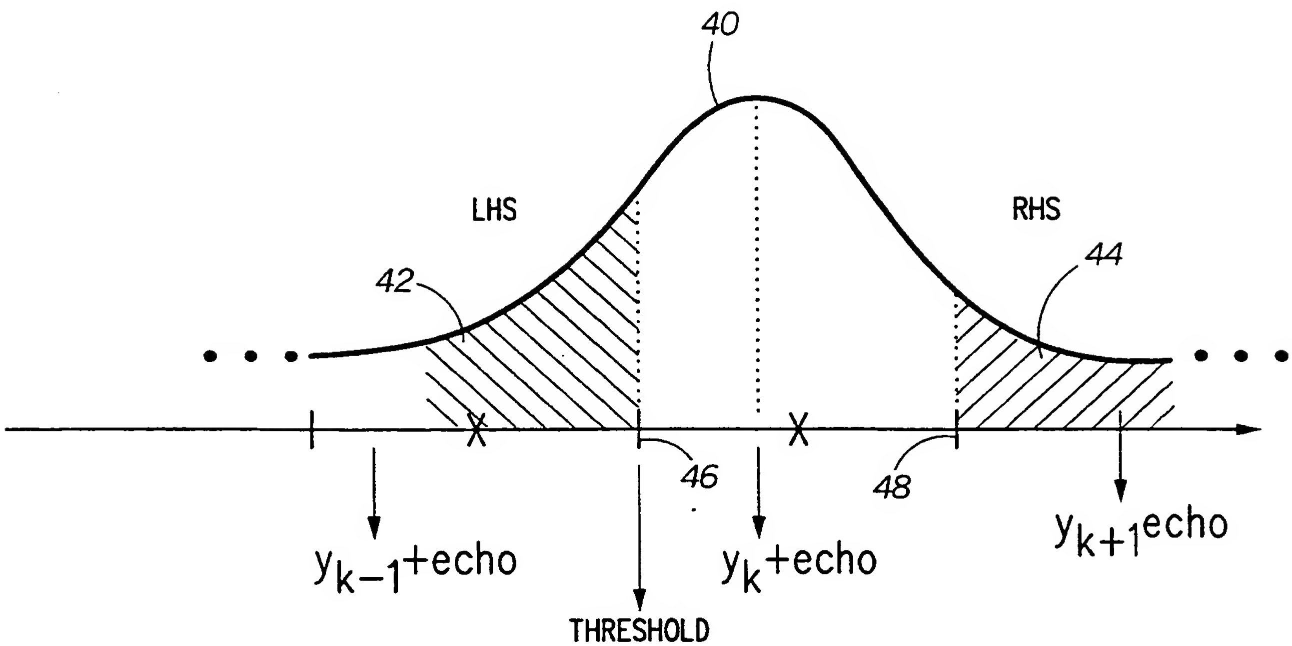
40
LHS
RHS
42
44
46
48
y_{k-1}+echo
y_k+echo
y_{k+1}echo
THRESHOLD

FIG. 5

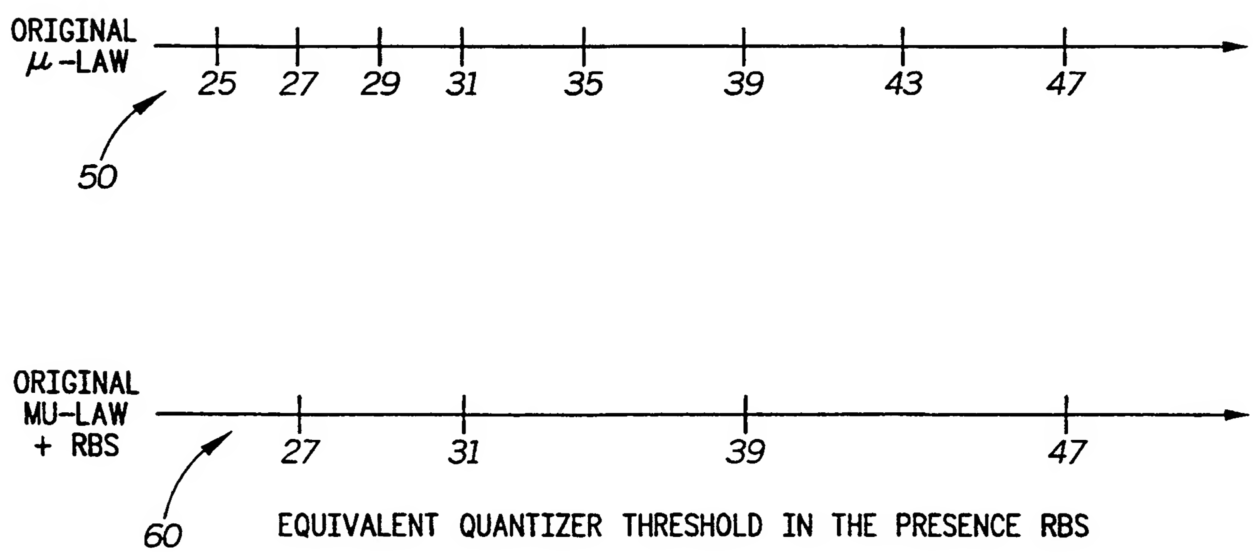
ORIGINAL
μ-LAW
25 27 29 31 35 39 43 47
50
ORIGINAL
MU-LAW
+ RBS
27 31 39 47
60
EQUIVALENT QUANTIZER THRESHOLD IN THE PRESENCE RBS

FIG. 6

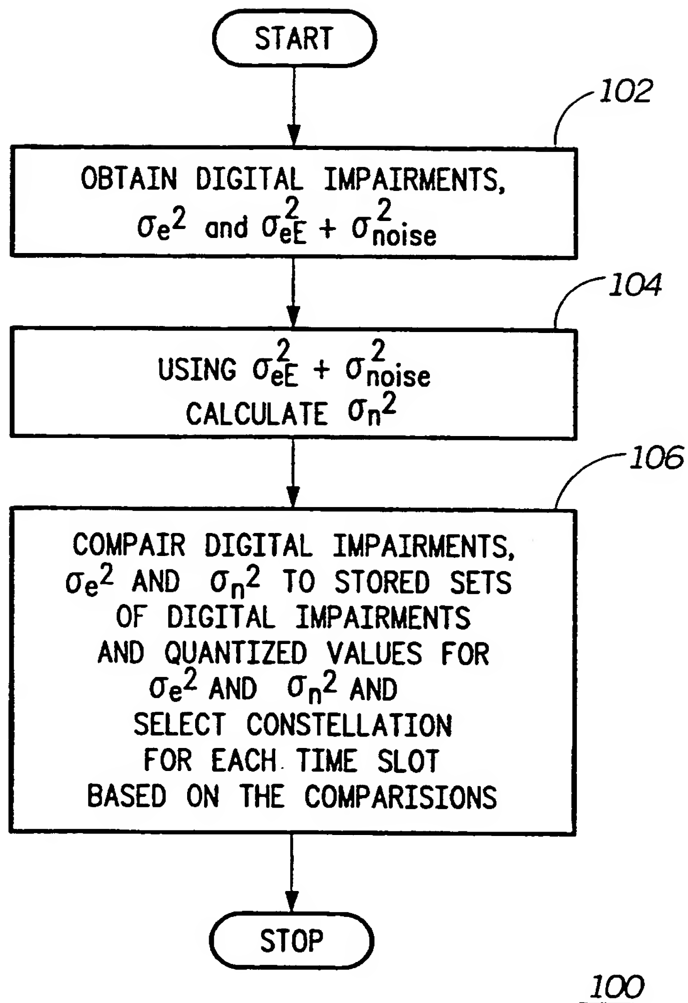
START
102
OBTAIN DIGITAL IMPAIRMENTS, σ_e^2 and $\sigma_{eE}^2 + \sigma_{noise}^2$
104
USING $\sigma_{eE}^2 + \sigma_{noise}^2$ CALCULATE σ_n^2
106
COMPAIR DIGITAL IMPAIRMENTS, σ_e^2 AND σ_n^2 TO STORED SETS OF DIGITAL IMPAIRMENTS AND QUANTIZED VALUES FOR σ_e^2 AND σ_n^2 AND SELECT CONSTELLATION FOR EACH TIME SLOT BASED ON THE COMPARISIONS
STOP
100

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/24369

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04L 27/04; H04B 14/04
US CL :375/295, 222, 242; 341/56
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 375/222, 241-243, 295-296, 298; 341/50, 56, 108, 110, 116, 126, 144, 155, 173

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS (analog modem, digital modem, pulse code modulation or PCM, and constellation point).

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,388,124 A (LAROIA et al.) 07 February 1995, col. 5, lines 20 to col. 6, line 2.	1-17
A	US 5,488,633 A (LAROIA) 30 January 1996, col. 2, line 28 to col. 3, line 19.	1-17
A	US 5,546,395 A (SHARMA et al.) 13 August 1996, col. 16, lines 37-67, and col. 17, line 47 to col. 18, line 24.	1-17

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
31 JANUARY 1999	12 APR 1999

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Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	YOUNG T. TSE
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